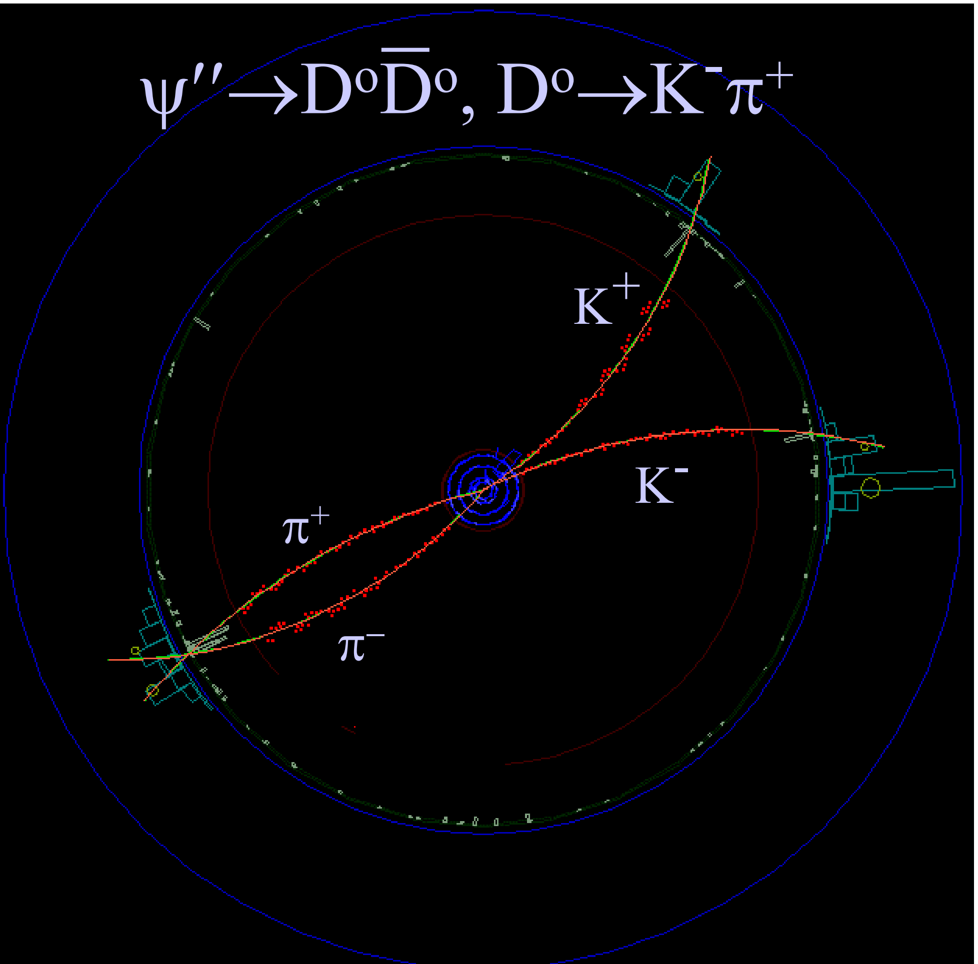
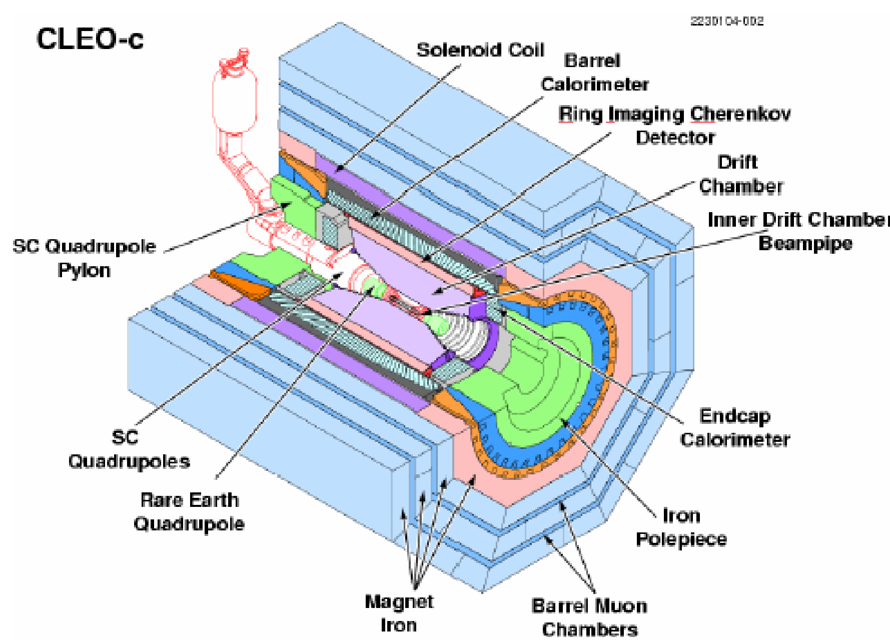
Leptonic & Semileptonic Decay Results from CLEO-c



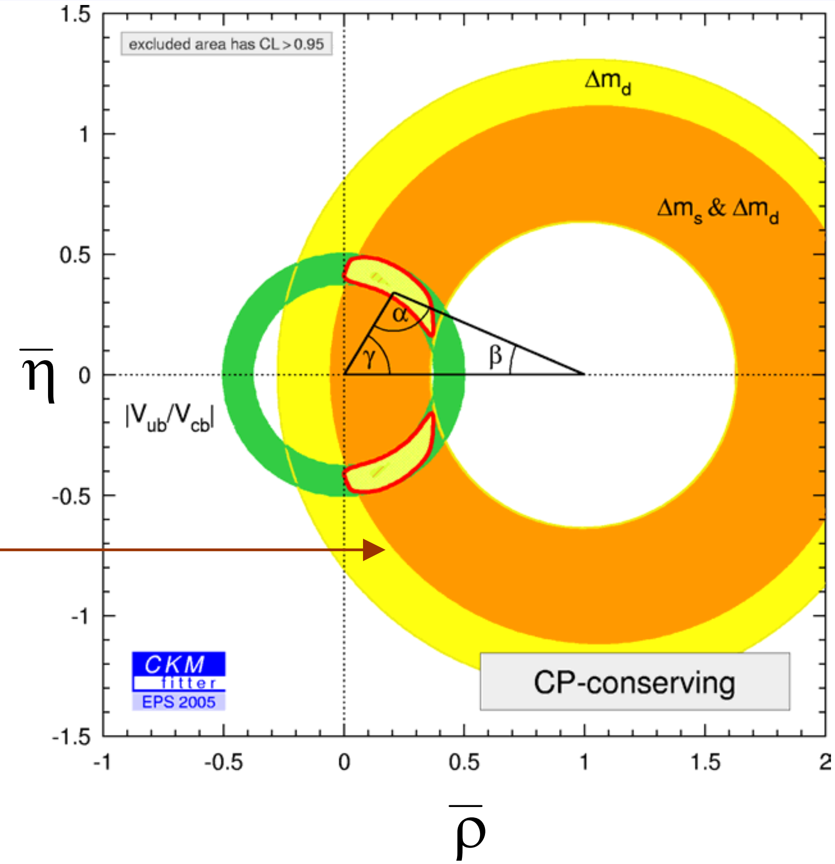
Sheldon Stone,
Syracuse University

"I charm you, by my once-commended beauty"
Julius Cæsar, Act II, Scene I



Goals in Leptonic Decays

- Test theoretical calculations in strongly coupled theories in non-perturbative regime
- f_B & f_{Bs}/f_B needed to improve constraints from Δm_d & $\Delta m_S/\Delta m_d$. Hard, if not impossible, to measure directly (i.e. $B \to \tau^+\nu$ or $\mu^+\nu$), but we can determine f_D & f_{Ds} using $D\to\mu^+\nu$ and use them to test theoretical models (i.e. Lattice QCD)



Goals in Semileptonic Decays

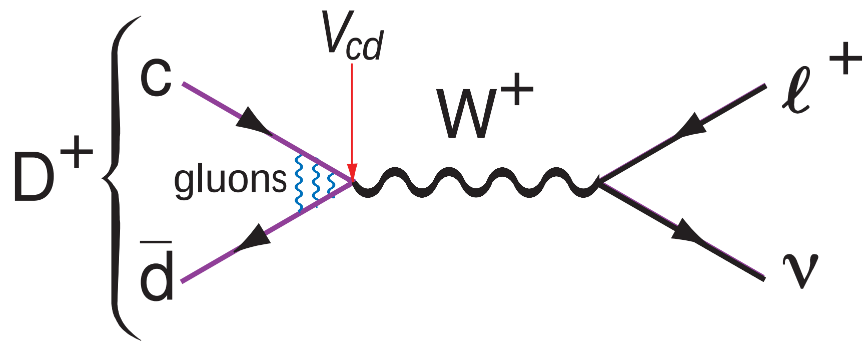
- Either take V_{cq} from other information and test theory, or use theory and measure V_{cq}
- V_{cs} use $D \rightarrow K(K^*)\ell\nu$ to measure form-factor shapes to distinguish among models & test lattice QCD predictions
- V_{cd} use $D \rightarrow \pi(\rho)\ell\nu$
- V_{cd} & V_{cs} with precise unquenched lattice predictions, + V_{cb} would provide an important unitarity check
- V_{ub} use $D \rightarrow \rho\ell\nu$ to get form-factor for $B \rightarrow \rho\ell\nu$, at same $v \bullet v$ point using HQET (& $\pi\ell\nu$)

Leptonic Decays: $D \to \ell^+ \nu$

Introduction: Pseudoscalar decay constants

c and $\bar{q}$ can annihilate, probability is $\propto$ to wave function overlap

Example :



In general for all pseudoscalars:

$$\Gamma(P^+ \to \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{Qq}|^2$$

Calculate, or measure if V_{Qq} is known

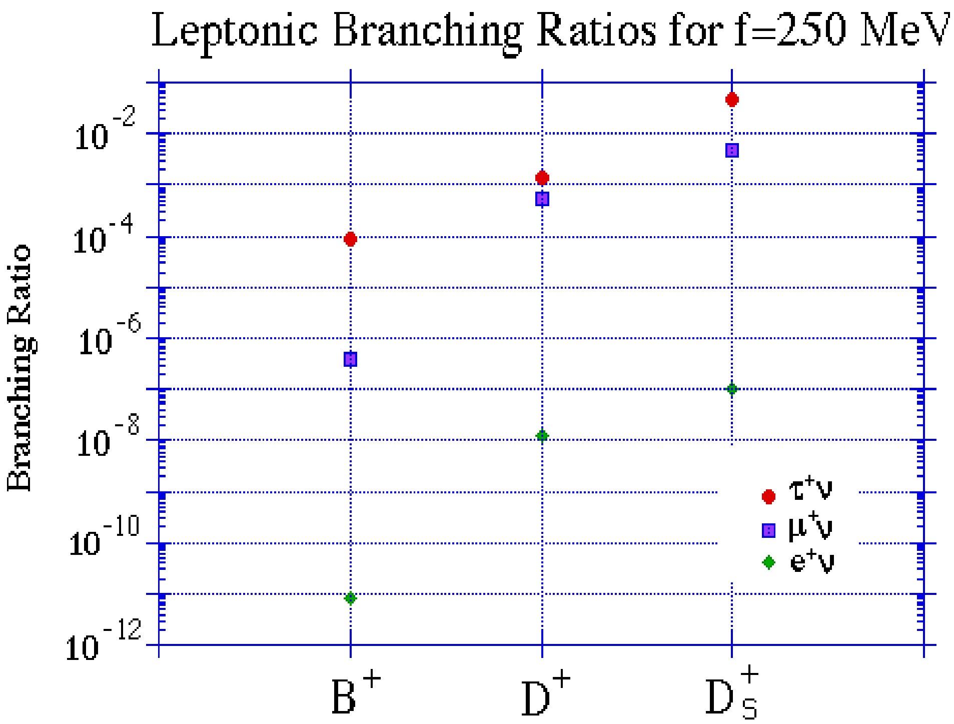
Expected $\mathcal{B}$ for $P^+ \to \ell^+ \nu$ decays

- We know:

  $f_\pi = 131.73 \pm 0.15$ MeV

  $f_K = 160.6 \pm 1.3$ MeV

- The D_s has the largest $\mathcal{B}$, for $\mu^+\nu$ rate is ~0.5%
- f_{Ds} Measured by several groups, best CLEO II, but still poorly known
- $e^+\nu$ rate is ~4 orders of magnitude smaller than $\mu^+\nu$, in the Standard Model

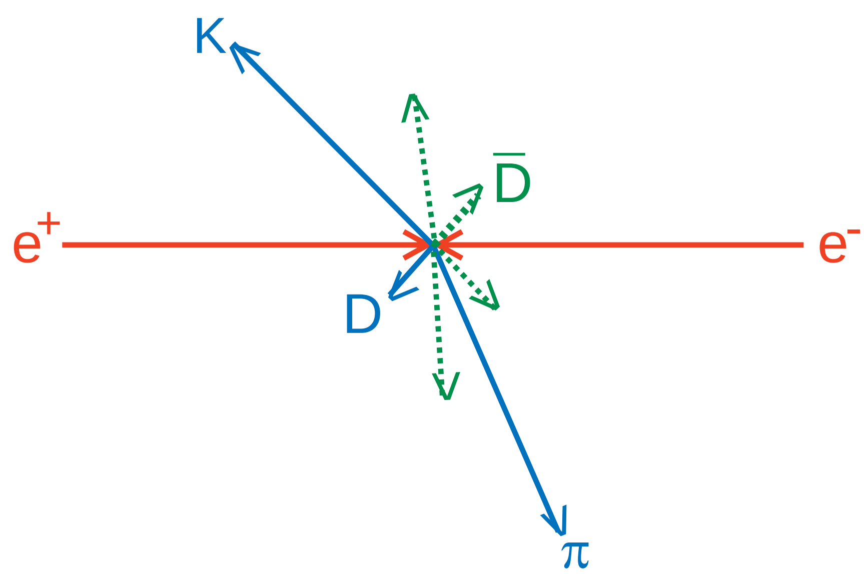


Kinematical Niceties

- Ease of $\mathcal{B}$ measurements using "double tags"

  $\mathcal{B}_A$ = # of A/# of D's

- Possible because
  - relatively large $\mathcal{B}$ (many %),
  - multiplicities typically small $\langle n_{charged}\rangle = \sim 2.5$, $\langle n_{\pi^o}\rangle \sim 1.2$,
  - enough luminosity

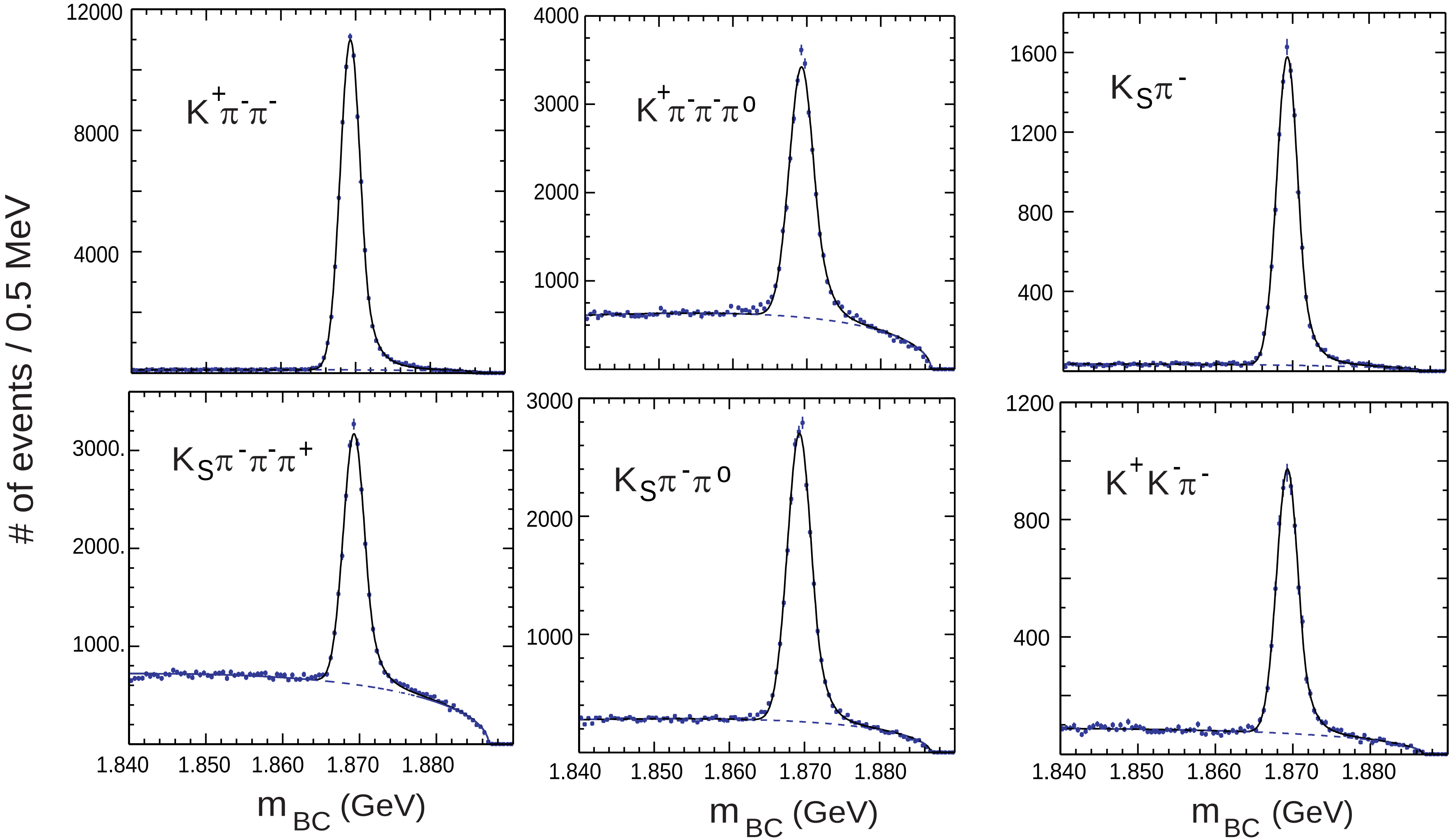


- Reconstruct single D mesons using:

$$m_{BC}^2 = \sum E_i^2 - \sum \vec{P}_i^2 = E_{beam}^2 - \sum \vec{P}_i^2$$

- Then find either a leptonic or semileptonic decay of the opposite D

D^- Candidates (in 281 pb^{-1})



# of tags = 158,354±496, includes charge-conjugate modes

Finding Leptonics & Semileptonics

- Ease of leptonic & semileptonic decays using double tags & Missing Mass^2 technique:

$$\mathrm{MM}^2 = (E_{D^+} - E_{\ell^+} - E_{hadrons})^2 - (\vec{p}_{D^+} - \vec{p}_{\ell^+} - \vec{p}_{hadrons})^2$$

We know $E_{D^+} = E_{beam}$, $\vec{p}_{D^+} = -\vec{p}_{D^-}$

- For leptonic decays

$$\mathrm{MM}^2 = (E_{beam} - E_{\ell^+})^2 - (-\vec{p}_{D^-} - \vec{p}_{\ell^+})^2$$

- Search for peak near $\mathrm{MM}^2=0$
- Since resolution ~ $M^2_{\pi^0}$, reject extra particles with calorimeter & tracking
- Sometimes people use $U_{miss} = E_{miss} - |\vec{P}_{miss}|$, for semileptonic decays

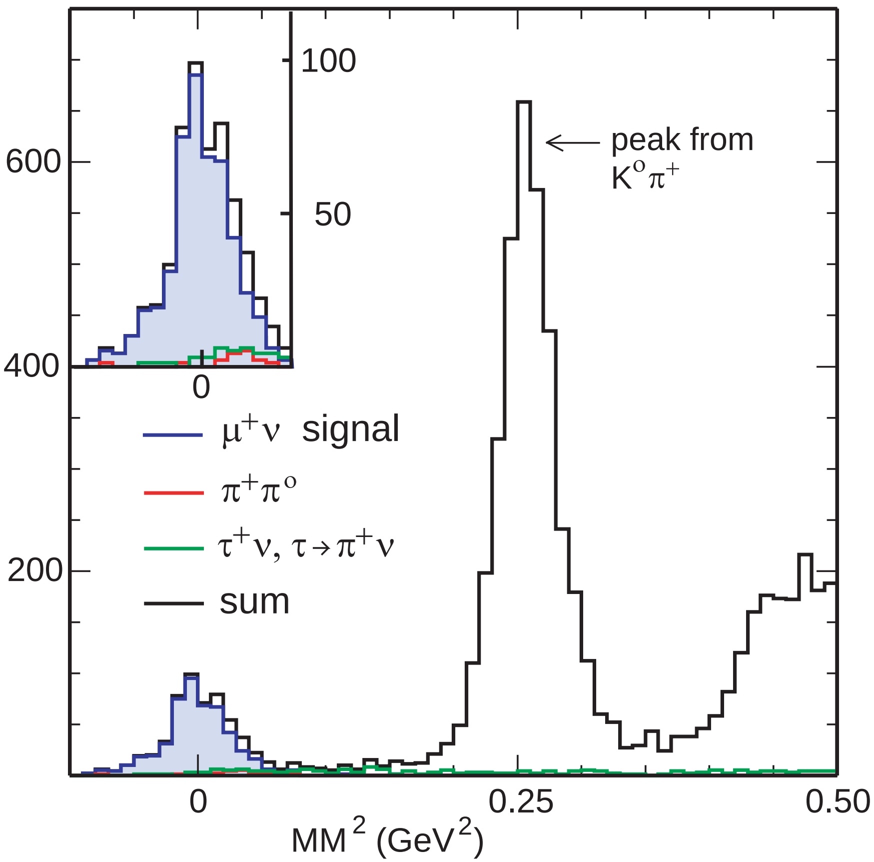
Technique for $D^+ \to \mu^+\nu$

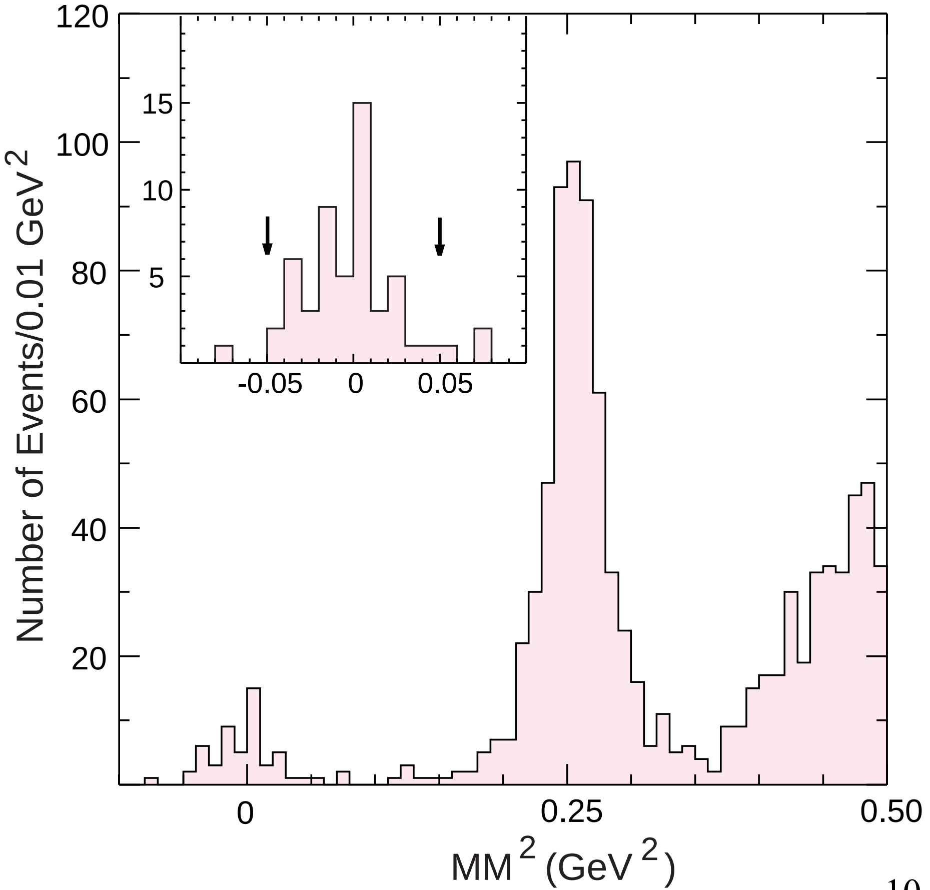
- Fully reconstruct one D^-, and count # of tags
- Seek events with only one additional charged track and no additional photons > 250 MeV to veto $D^+ \to \pi^+\pi^o$
- Charged track must deposit only minimum ionization in calorimeter
- Compute MM^2. If close to zero then almost certainly we have a $\mu^+\nu$ decay. Evaluate backgrounds
- Evaluate efficiencies
- Evaluate Systematic errors

Measurement of f_{D^+}

MC Expectations from 1.7 fb^{-1}, 30 X of our data

Data: 50 events in the signal region in 281 pb^{-1}





Deriving a Value for f_{D^+}

Backgrounds		
Mode	$\mathcal{B}(\%)$	# Events
$\pi^+\pi^0$	0.13 ± 0.02	$1.40\pm0.18\pm0.22$
$K^0\pi^+$	2.77 ± 0.18	$0.33\pm0.19\pm0.02$
$\tau^+\nu$ ($\tau\rightarrow\pi^+\nu$)	$2.65 * \mathcal{B}(D^+\rightarrow\mu^+\nu)$	$1.08\pm0.15\pm0.16$
Other D^+, D^o		<0.4, <0.4 @ 90% c.l.
Continuum		<1.2 @ 90% c.l.
Total		$2.81\pm0.30^{+0.84}_{-0.27}$

- There are 158,354 tags. ε= 67.7%
- $\mathcal{B}(D^+\rightarrow\mu^+\nu) = (4.40\pm0.66^{+0.09}_{-0.12})\text{x}10^{-4}$
- $f_{D^+} = (222.6\pm16.7^{+2.3}_{-3.4})$ MeV
- $\mathcal{B}(D^+\rightarrow e^+\nu) < 2.4\text{x}10^{-5}$ @ 90% c.l., rules out some non-Standard model theories

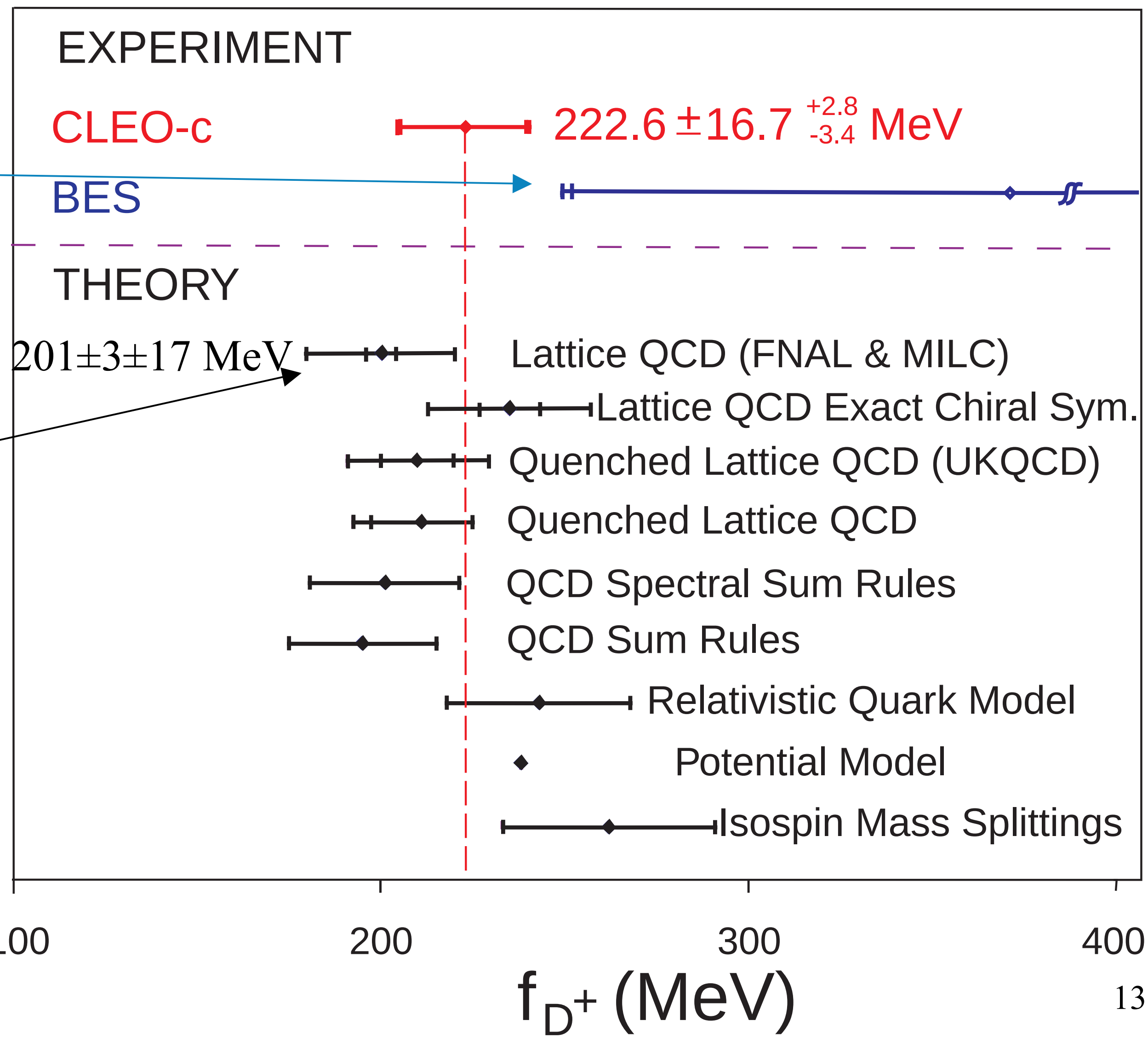
Efficiencies: μ^+ detection (69.4%); extra shower (96.1%); correction for easier tag reconstruction in $\mu^+\nu$ events (1.5%)

Systematic Errors

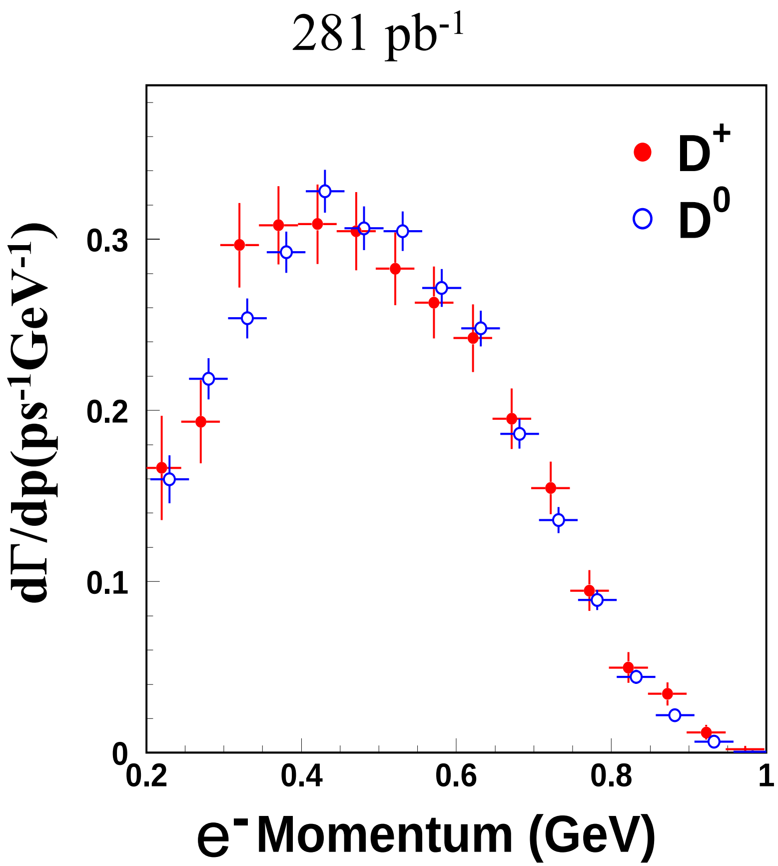
Source of Error	%
Finding the μ^+ track	0.7
Minimum ionization of μ^+ in EM cal	1.0
Particle identification of μ^+	1.0
MM^2 width	1.0
Extra showers in event > 250 MeV	0.5
Background	0.6
Number of single tag D^+	0.6
Monte Carlo statistics	0.4
Total	**2.1**

Comparison to Theory

- BES measurement based on 2.67±1.74 events
- Current Lattice measurement (unquenched light flavors) is consistent
- But systematic errors on theory & statistical errors on data are still large



Inclusive semileptonic branching fractions



Lab momentum spectrum – no FSR correction

- Tagged sample: only "golden modes" $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$
- Identify *e*, π, K right-sign and wrong-sign samples, use unfolding matrix→true *e* population.
- Correction for p_e- cut

$$B(D^+ \to Xe\nu) = (16.19 \pm 0.20 \pm 0.36)\%$$

$$\sum B(D^+ \to Xe\nu)_{excl} = (15.1 \pm 0.50 \pm 0.5)\%$$

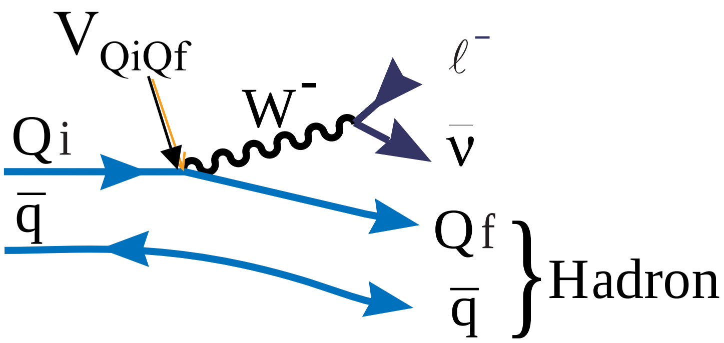
$$B(D^0 \to Xe\nu) = (6.45 \pm 0.17 \pm 0.15)\%$$

$$\sum B(D^0 \to Xe\nu)_{excl} = (6.1 \pm 0.2 \pm 0.2)\%$$

$$\frac{\Gamma(D^+ \to Xe^+\nu)}{\Gamma(D^o \to Xe^+\nu)} = 1.01 \pm 0.03 \pm 0.03$$

Exclusive Semileptonic Decays

- Best way to determine magnitudes of CKM elements, in principle is to use semileptonic decays. Decay rate $\alpha |V_{QiQf}|^2$



- This is how V_{us} (λ) and V_{cb} (A) have been determined
- Kinematics: $q^2 = \left(p_D^\mu - p_{hadron}^\mu\right)^2 = m_D^2 + m_P^2 - 2E_P m_D$
- Matrix element in terms of form-factors (for D→Pseudoscalar $\ell^+ \nu$

$$\left\langle P(P_P) \middle| J_\mu \middle| D(P_D) \right\rangle = f_+(q^2)(P_D + P_P)_\mu + f_-(q^2)(P_D - P_P)_\mu$$

- For ℓ = e, contribution of $f\_(q^2) \rightarrow 0$

Combining Semileptonics & Leptonics

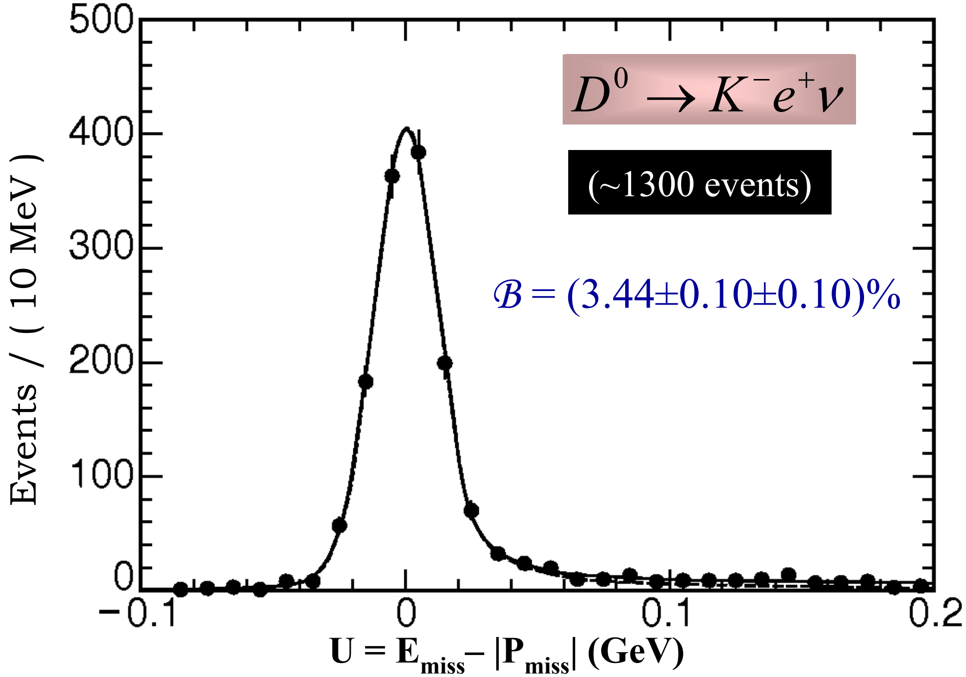
- Decay rate:

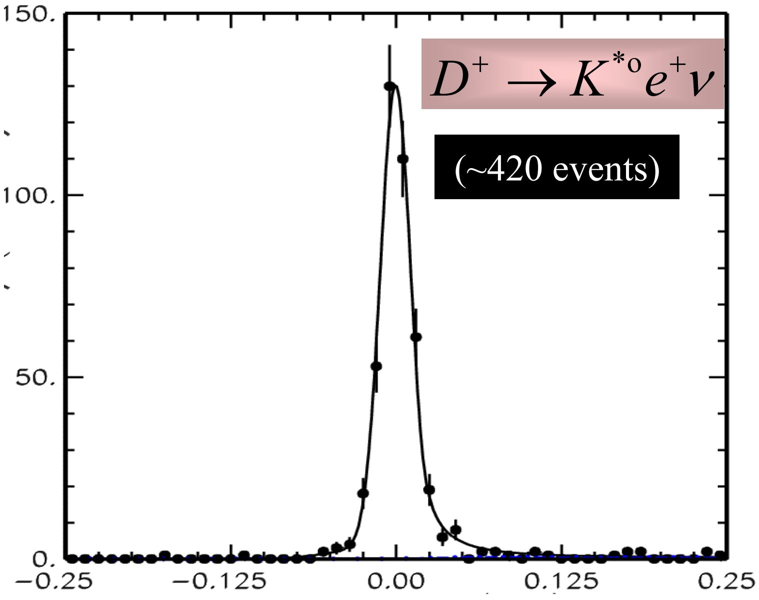
$$\frac{d\Gamma\left(D \to P e \nu\right)}{dq^2} = \frac{\left|V_{cq}\right|^2 P_P^3}{24\pi^3} \left|f_+(q^2)\right|^2$$

- Test of models in D decays: predictions of shapes of form factors (for D→Vector $\ell^+\nu$ there are 3 form-factors)
- Note that the ratio below depends only on QCD:

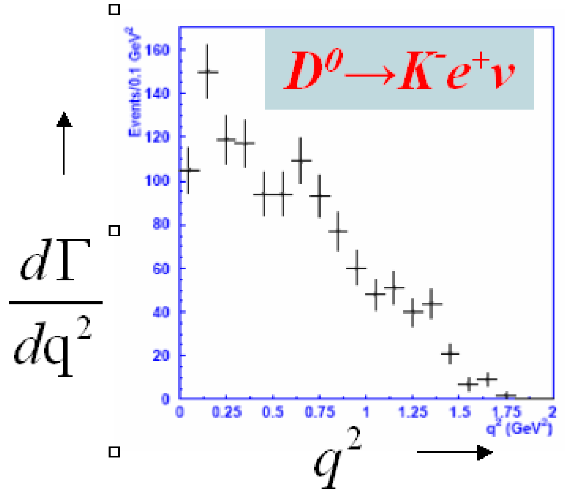
$$\frac{1}{\Gamma\left(D^+ \to \ell \nu\right)} \frac{d\Gamma\left(D^+ \to \pi e \nu\right)}{dq^2} \;\alpha\; \frac{P_\pi^3 \left|f_+(q^2)\right|^2}{f_{D^+}^2}$$

Cabibbo Favored Semileptonic Decays





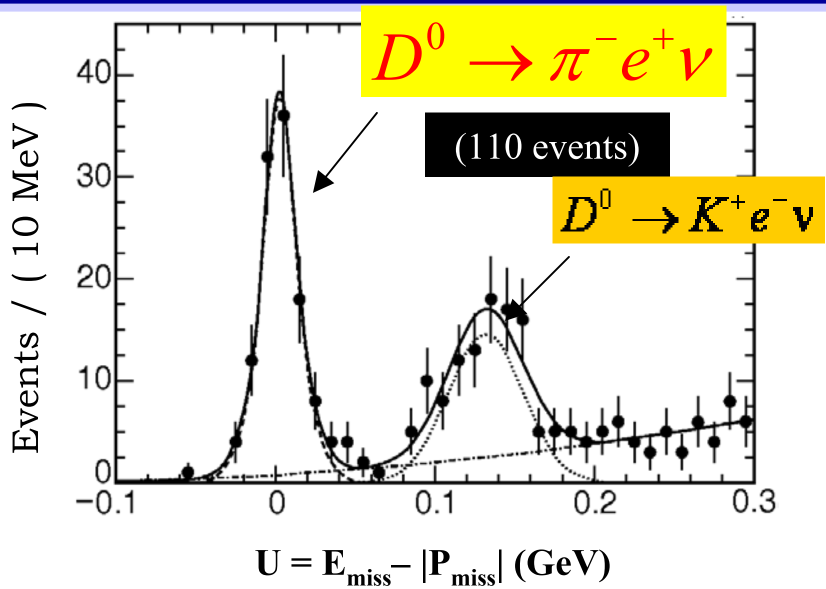
$\mathcal{B} = (5.70\pm0.28\pm0.25)\%$

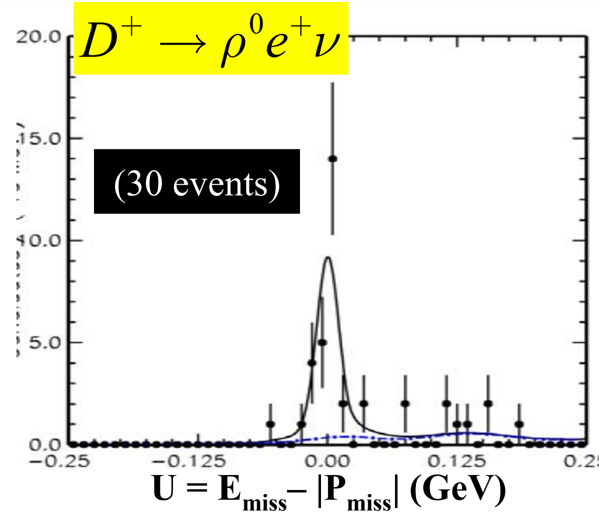


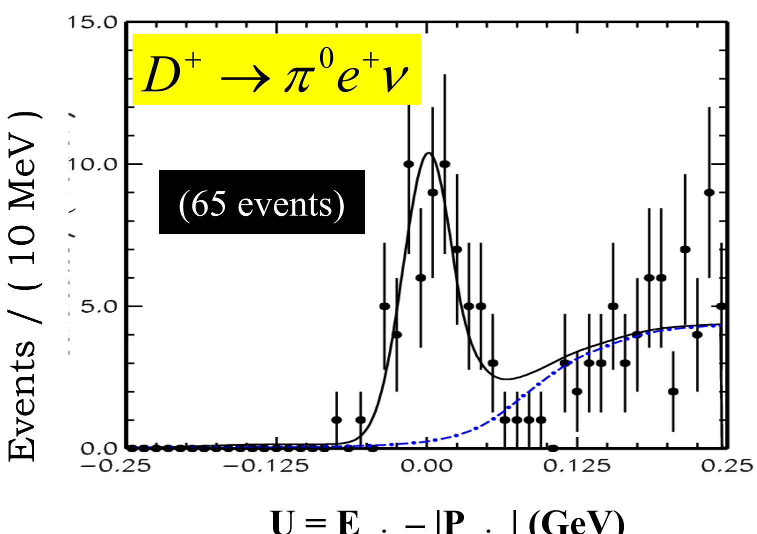
Raw q^2 → No efficiency correction, results soon

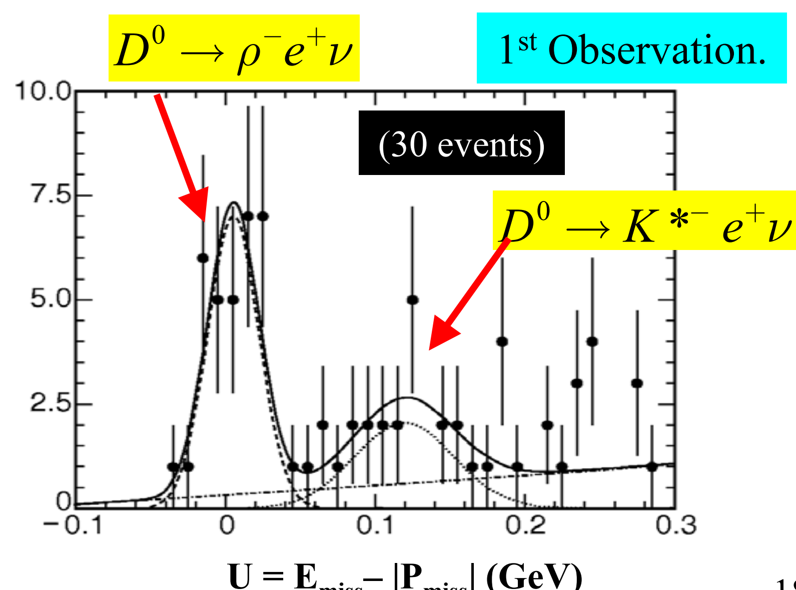
These are the dominant modes, so backgrounds are almost non-existent

Cabibbo Suppressed Semileptonic Decays





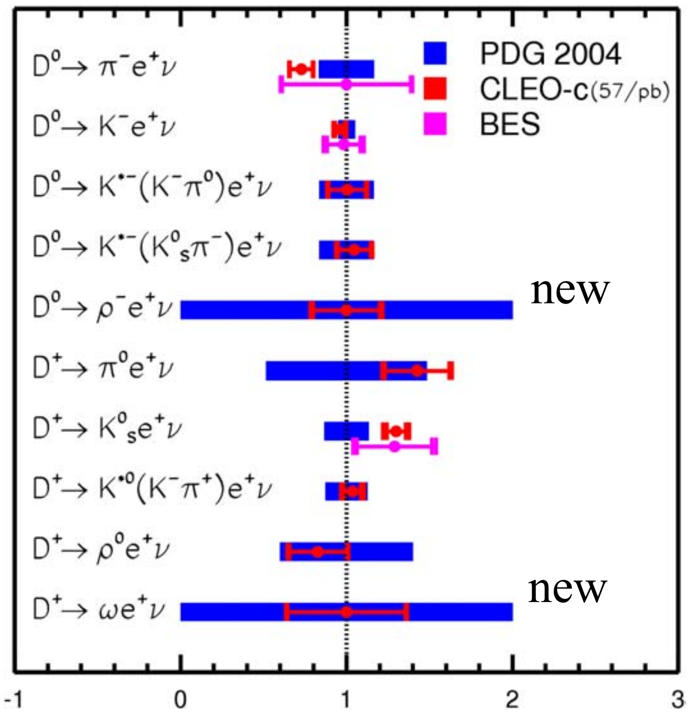




Summary of Semileptonic Branching Ratio Results

	Decay Mode	$\mathcal{B}$ (%) (CLEO-c/(57/pb))	$\mathcal{B}$ (%) (PDG-04)
1.	$D^0 \to \pi^- e^+ \nu$	$0.26 \pm 0.03 \pm 0.01$	0.36 ± 0.06
2.	$D^0 \to K^- e^+ \nu$	$3.44 \pm 0.10 \pm 0.10$	3.58 ± 0.18
3.	$D^0 \to K^{*-}(K^-\pi^0) e^+ \nu$	$2.16 \pm 0.24 \pm 0.11$	2.15 ± 0.35
4.	$D^0 \to K^{*-}(K^0_S\pi^-) e^+ \nu$	$2.25 \pm 0.21 \pm 0.11$	2.15 ± 0.35
5.	$D^0 \to \rho^- e^+ \nu$	$0.19 \pm 0.04 \pm 0.02$	—
6.	$D^+ \to \pi^0 e^+ \nu$	$0.44 \pm 0.06 \pm 0.03$	0.31 ± 0.15
7.	$D^+ \to \bar{K}^0 e^+ \nu$	$8.71 \pm 0.38 \pm 0.37$	6.7 ± 0.9
8.	$D^+ \to \bar{K}^{*0}(K^-\pi^+) e^+ \nu$	$5.70 \pm 0.28 \pm 0.25$	5.5 ± 0.7
9.	$D^+ \to \rho^0(\pi^+\pi^-) e^+ \nu$	$0.21 \pm 0.04 \pm 0.02$	0.25 ± 0.10
10.	$D^+ \to \omega(\pi^+\pi^-\pi^0) e^+ \nu$	$0.17 \pm 0.06 \pm 0.01$	—

Ratio to PDG



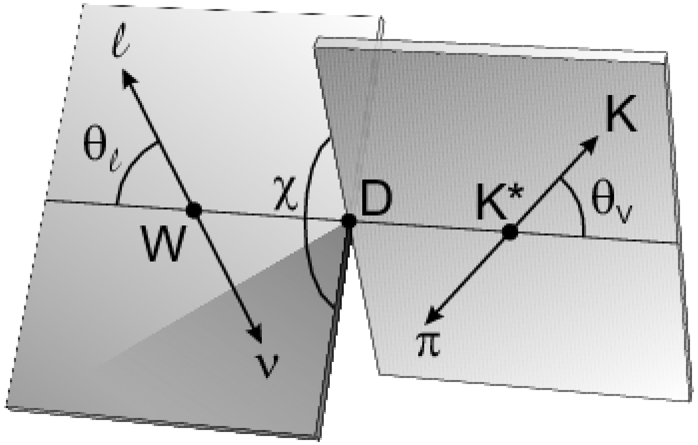
- Using unquenched lattice (hep-ph/0408306) find
- $V_{cs} = 0.956 \pm 0.036 \pm 0.093 \pm 0.017$
- $V_{cd} = 0.213 \pm 0.008 \pm 0.020 \pm 0.008$

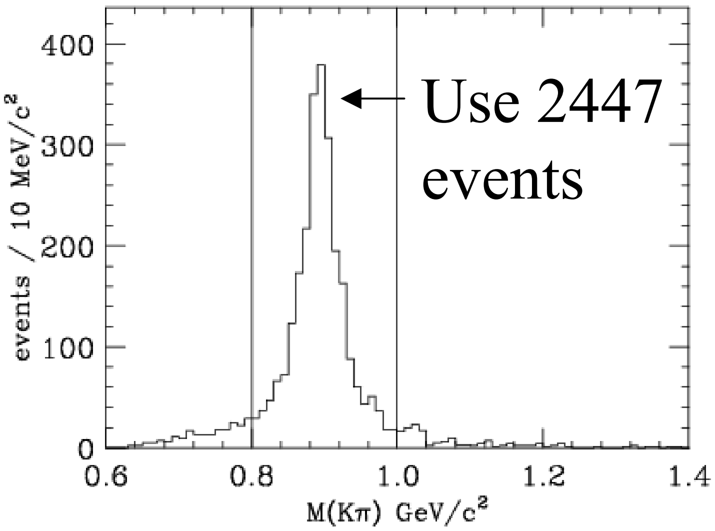
stat	sys	exp
lat	lat	CLEO-c

V_{cs} (LEP) = 0.976 ± 0.014
$V_{cd}(\nu N)$ = 0.224 ± 0.012
Currently this checks Lattice calculations

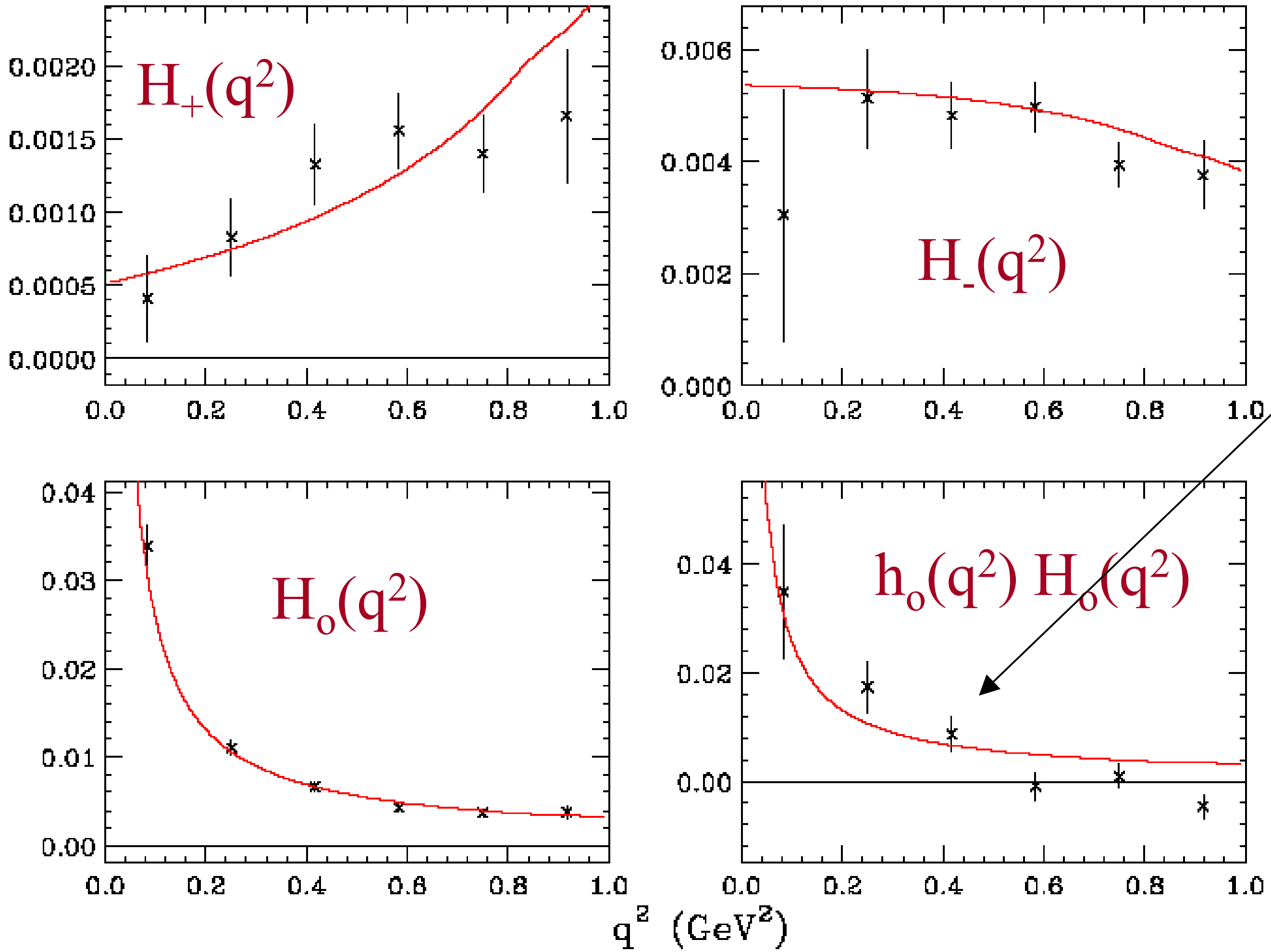
$D^+ \to K^- \pi^+ e^+ \nu$ Form Factors

- $K^- \pi^+$ mostly K^* with some s-wave (1st seen by FOCUS)
- For $D \to V e^+ \nu$, use 3 helicity amplitudes $H_o(q^2)$, $H_+(q^2)$, & $H_-(q^2)$
- Add $h_o(q^2) \bullet H_o(q^2)$ to account for s-wave term
- Use 281 pb^{-1}





Form Factor Results



- Significant s-wave amplitude confirmed
- Parameter-ization not great
- No evidence for d or f wave

Lattice comparison: f_D and semileptonic form factors

- We can use a quantity independent of V_{cd} to do a CKM independent lattice check:

$$R_{\ell sl} \equiv \sqrt{\frac{\Gamma(D^+ \to \mu\upsilon)}{\Gamma(D^+ \to \pi\ell\upsilon)}} \propto \frac{f_D}{f_+^{\pi}(0)}$$

- I obtain:

$$R_{\ell sl}^{th} = 0.22 \pm 0.02$$

$$R_{\ell sl}^{\exp} = 0.25 \pm 0.02$$

- Theory and data consistent at ~30% C.L.

Conclusions

- $\mathcal{B}(D^+ \to \mu^+\nu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4}$
- $f_{D^+} = (222.6 \pm 16.7^{+2.3}_{-3.4})$ MeV, consistent with unquenched lattice QCD (hep-lat/0506030)
- More data coming including $D_S^+ \to \mu^+\nu$
- $\mathcal{B}(D^+ \to e^+\nu) < 2.4 \times 10^{-5}$ @ 90% c.l.
- World's best semileptonic branching ratios in most modes with only 20% of available data; will be updated soon along with form-factor measurements